ANALYSIS AND CONTROL OF PROCESSES

A Thesis Submitted in Partial Fulfilment
of the Requirements for the Award of the Degree of

Bachelor of Technology
in
Electronics and Instrumentation Engineering

by
ANURAN MAITI
Roll No: 109EI0073

Under the Supervision of
Prof. Umesh Chandra Pati

Department of Electronics & Communication Engineering
National Institute of Technology, Rourkela
Odisha- 769008, India
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CERTIFICATE

This is to certify that the Thesis Report entitled "**ANALYSIS AND CONTROL OF PROCESSES"** submitted by **ANURAN MAITI** bearing roll no. **109EI0073** in partial fulfilment of the requirements for the award of Bachelor of Technology in Electronics and Instrumentation Engineering carried out during the academic session 2012-2013 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date: Dr. Umesh Chandra Pati

Associate Professor
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Rourkela-769008

Dedicated to My Parents

And

Indian Philosophy of Life

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First of all, I would like to express my deep sense of respect and gratitude towards my advisor and guide **Prof. Umesh Chandra Pati**, who has been the guiding force behind this work. Also the subject "Process Control" taught by him in depth and clarity is an integral part of this project work. I am greatly indebted to him for his constant encouragement, invaluable advice and for propelling me further in every aspect of my academic life. His presence and optimism have provided an invaluable influence on my career. I consider it my good fortune to have got an opportunity to work with such a wonderful person, not just professionally but personally as well.

I want to express my respects to Prof. T. K. Dan for teaching "Advance Process Control" without which this project could not have been completed successfully. I thank each and every faculty of the Department of Electronics and Communication Engineering, National Institute of Technology, Rourkela from the bottom of my heart. They have been great sources of inspiration, knowledge and encouragement throughout the course of Bachelor's Degree.

I am indebted to my parents for their love, sacrifice, and support. They are my first teachers and have set great examples and taught me the life lessons of hard work, dedication and how to live with conviction.

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ABSTRACT

In any processes industry, the main and primary variable and processes that needs to be controlled are temperature, level, pressure and flow. This project deals with control and analysis of the first three. Before beginning with any kind of analysis of a system, it needs to be mathematically modelled. Laplace transfer and linearization forms the two most important part of this modelling which is carried out in each and every system considered in this project work. Also higher-order systems can be distinguished on the basis of their non-interacting or interacting nature.

In level process, firstly, a single-tank system is considered where the objective is to maintain the process liquid at a desired level or change it at a pre-determined rate by controlling the manipulated variables, firstly one at a time and then all of them being controlled simultaneously at the same time. This is a non-interacting system. Next, a two-tank system is analysed where the objective is two maintain the process liquid in the second tank by controlling the manipulated variables which affect the first tank. Here two types of system are considered; interacting and non-interacting. Following this a three-tank, non-interacting system is modelled where the level of the third tank is maintained by manipulated variables affecting the first tank. The responses curves of these systems to various forcing functions such as step, sinusoidal and ramp are generated analysed.

In thermal process, the work begins with modelling an adiabatic process followed by a non-adiabatic process. The dynamics of the process is understood by analysing the feature of the solution. The control objective is to maintain the process fluid temperature at the desired value by controlling the manipulated variables (such as inlet flow, coolant temperature etc.).

The response curves of these systems are generated to different forcing functions.
The objective in gas process was to maintain a gas vessel at desired pressure and its modelling is followed by generating responses to various forcing functions.

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is used to simulate all these processes. Rapid advances in software/hardware technologies and virtualizations of instruments have led to its becoming an integral part of many control strategies

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LIST OF ABBREVIATIONS

LabVIEW	Laboratory Virtual Instrumentation Engineering Work Bench
MIMO	Multiple Input Multiple Output
SISO	Single Input Single Output
VI	Virtual Instrumentation

CHAPTER-1

INTRODUCTION

1.1 Overview

1.2 Literature Review

1.3 Motivation

1.4 Objective

1.5 Organization of Thesis

This chapter is dedicated to provide the overview of the project. It consists of brief description of level, thermal and gas process. This is followed by literature survey. The objectives and organization of the thesis is mentioned after this.

1.1 OVERVIEW

An important part of process industry is the control of chemical processes by the help of various input variables classified as either manipulated or disturbance variables. A manipulated input is one that can be adjusted by the control system while a disturbance input is a variable that affects the process outputs. The major processes that needed to be controlled are level, thermal, gas etc. These are also, often the measured variables and are commonly the controlled variable.

Before developing the control strategy or obtaining the response to different forcing function any system must be mathematically modelled. A mathematical model can be defined as "A set of equation (including the necessary input data to solve the equations) that allows us to predict the behaviour of a chemical process." Models play a very important role in control-system design. They can be simulate expected process behaviour with a proposed control system.

Linearization is an important component in mathematical modelling. A major difficulty in analysing the dynamic response of many processes is that they are non-linear, that is, they cannot be represented by linear differential equations. Linearization approximates the response of non-linear systems with linear differential equation that can be analysed by Laplace Transforms. The linearized approximation of the non-linear equation is valid for a region near some base point around which the linearization is made.

The next work is defining the control objective. This consists of knowing the requirement of the process. This can be maintaining the temperature, level, and pressure etc. at a desired value or increment/decrement at a certain pre-determined rate.

Level processes are perhaps the most common of all the processes. Owing to safety or process condition the level of the process liquid must be maintained at a certain level in spite of the disturbances. These processes are non-linear, multivariable and time varying. It can be a simple process such as a single-tank level control to complex ones, such as two-tank to even more complex three-tank control. The level control process can be further subdivided into interacting or non-interacting process. In two-tank interacting system, the level of one tank depends on the other in addition to the disturbance and manipulated variables unlike in the case of non-interacting systems.

Thermal processes are encountered equally frequently. Maintaining the temperature at a desired value of the process liquid is usually the control objective in most cases. The disturbances and manipulated variables are usually inlet temperature of liquid and coolant temperature. Thermal processes can be further sub divided into adiabatic and non-adiabatic process depending on if there is heat loss to surrounding or not.

Lastly, the gas process, commonly encountered as pressure control problem has equally wide application. Maintaining the pressure of the vessel at a desired value or increasing/decreasing it a certain pre-determined rate is the primary control objective in such process.

These systems are subjected to different types of commonly encountered forcing function i.e. step, sinusoidal, ramp etc. and the response of the system is obtained and analysed. The response depends on the characteristic equations and the values of the constants (i.e. density of process liquid, base values of level, valve coefficient etc.) involved.

LabVIEW (Laboratory Virtal Instrumentation Engineering Workbench) is generally used to communicate with hardware such as data acquisition, instrument control and industrial automation. Rapid advances in software/hardware technologies and virtualizations of instruments have led to its becoming an integral part of many control strategies. LabVIEW provides a graphical programming environment against the more complex and time consuming text-code based programming. The simulations and response generation of all the systems discussed in this work has been done using LabVIEW.

1.2 LITERATURE REVIEW

The literature study of this project began with understanding the procedure of mathematical modelling [1] and understanding the level, thermal, gas process [2] in terms of its control. This was followed by learning the procedure of implementing a mathematical model in LabVIEW [3-5]. In the paper titled "Realization of Liquid Level Real-time Control System based on LabVIEW", *Min Li, Xing Wen Chen & Yan Liu* [6] LabVIEW is used as developing environment and virtual instrumentation as developing method to realize liquid level real time control system while in the paper "LabVIEW and internet Based remote Water control Laboratory", *Lin Gao & Jianqun Lin* [7], control panel of Water level control system is embedded in a web page which was implemented in LabVIEW and through which remote user can change the set point. Practical implications of computers upon the established method currently used to control temperature in industrial process is underlined in the paper "Temperature Control strategies for Industrial Process", *William K. Roots and Malayappan Shridhar* [8]. In the paper titled "Analysis of Higher-Order Thermal Process using LabVIEW", S.B. Prusty, U.C. Pati [9], a higher order MIMO (multiple input-multiple output) thermal system is modelled and simulated using LabVIEW.

1.3 MOTIVATION

In any process industry the important variable that needs to be controlled are level, temperature, pressure etc. Dynamic response of any process is the prime consideration in design, analysis & implementation of process control. The dynamics changes from one process to another. The control performance provided by the controller depends on the adjustment or specifications of different terms in controller. Setting these terms is called Tuning**.** Optimum tuning results in optimum performance by the controller. We can tune the controller only after steady state and the dynamic characteristics are known. Almost all of these processes are non-linear and multivariable in nature and hence prior linearization is required. For linearization, Taylor series expansion around base values is done. Also the simulation results give an indication to the extent of change in controlled variable with the change of disturbances. This helps and gives clues for deciding upon which control strategy can result in optimum performance of the controller. The response of these systems to various forcing function give an indication to their characteristics such as time constant etc.

1.4 OBJECTIVES

The objectives of this thesis are:

- To develop the mathematical model.
- Linearize multivariable non-linear process.
- To keep the level of liquid in tank at desired value.
- To maintain the temperature of a process liquid at a desired value.
- To maintain the pressure of a vessel at a desired value.
- Analyse responses to various forcing functions to these systems.

1.5 ORGANISATION OF THE THESIS

Including the introductory chapter, this thesis comprises of 5 chapters. The organisation of the thesis is presented below.

Chapter-2 Level Process

First, Second and third order system are discussed and modelled. First and third order system are non-interacting while for the case of second order two-tank system both interacting and non-interacting process are modelled and implemented in LabVIEW. This is followed by subjecting each of the system to 3 types of input forcing functions i.e. step, sinusoidal and ramp.

Chapter-3 Thermal Process

First order thermal process is considered in this work. The thermal processes are of mainly two types, adiabatic and non-adiabatic. Each of them have been mathematical modelled and implemented in LabVIEW and subjected to same set of forcing functions (step, sinusoidal and ramp).

Chapter-4 Gas Process

First order gas process is modelled from its characteristic equation and implemented in LabVIEW and subjected to different forcing functions.

Chapter-5 Conclusions

The final conclusions of the work done along with the scope for future work are presented in this chapter.

CHAPTER-2

LEVEL PROCESS

This chapter includes mathematical modelling, implementation in LabVIEW, obtaining the front panel simulations and response to input forcing functions for first order 1-tank system, second order 2-tank system (interacting and non-interacting) and higher order 3-tank systems (non-interacting).

2.1 First Order Single Tank System

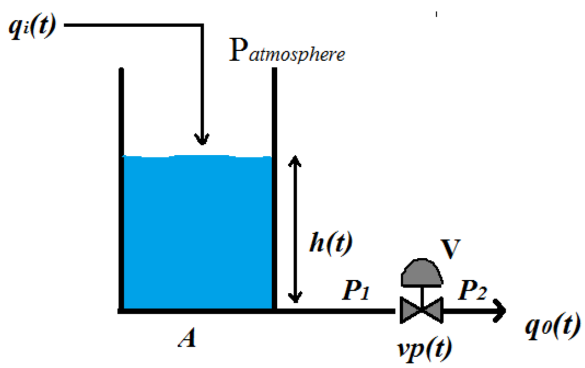


Fig.1: First Order Level Process

Where,

q_i = Inlet volumetric flow rate [m^3/sec]

q_o = Outlet volumetric flow rate [m^3/sec]

C_V= Valve Coefficient

h = Height of liquid in the tank [m]

ρ = Liquid density [Kg/m^3]

A = Cross sectional area of the tank [m^2]

G = Specific gravity of the liquid

The system is a single tank having an inlet flow $q_i(t)$ m^3/s and an outlet valve V whose position $vp(t)$ both of which can be controlled to maintain the level of the liquid $h(t)$ at a desired value. The variation in level of tank is plotted against time as these two controlled variables are changed. This is a non-interacting and SISO system.

2.1.1 Mathematical Modelling

Unsteady mass balance equation for the contents of the tank is

$$\rho q_i(t)-\rho q_0(t) = \frac{dm(t)}{dt} = A\rho \frac{dh(t)}{dt} \tag{1}$$

The flow through the valve, q_0 (m^3/s) is given by

$$q_0(t) = Cv.vp(t)\sqrt{\frac{P1+\rho g h(t)-P2}{G}} \tag{2}$$

Where Valve Coefficient is given as

$$Cv = 11.7\ q(t)\ .\sqrt{\frac{G}{dP}}\ \text{(in SI units)} \tag{3}$$

Eq. (1) after being linearized by using Taylor series can be written in terms of deviation variable after using the value of $q_0(t)$ from Eq. (2) and Cv from Eq. (3) as

$$\mathbf{Q}_i - [C_1\mathbf{VP}(t) + C_2\mathbf{H}(t)] = A\frac{d\boldsymbol{H}(\boldsymbol{t})}{dt} \tag{4}$$

Taking the Laplace transform of Eq. (4) and rearranging the terms

$$H(s) = \mathbf{Q}_i(s)\frac{K1}{\tau s+1} + \mathbf{VP}(s)\frac{-K2}{\tau s+1} \tag{5}$$

After substituting the values ($\bar{h}$=0.5m, $\overline{vp} = 0.5$), we obtain

$$H(s) = \mathbf{Q}_i(s)\frac{0.1019}{\tau s+1} + \mathbf{VP}(s)\frac{-1}{\tau s+1} \tag{6}$$

2.1.2 Simulations

The first order level process is designed and simulated using LabVIEW. The block diagram and front panel are shown in Fig. 2 and Fig. 3 respectively. As the inlet flow $q_i(t)$ is increased, the level of water in the tank $h(t)$ increases and when the valve position of the outflow valve *vp(t)* is increased, the level of water in the tank decreases. The level of liquid in the tank is plotted against the simulation time and has been shown in the front panel.

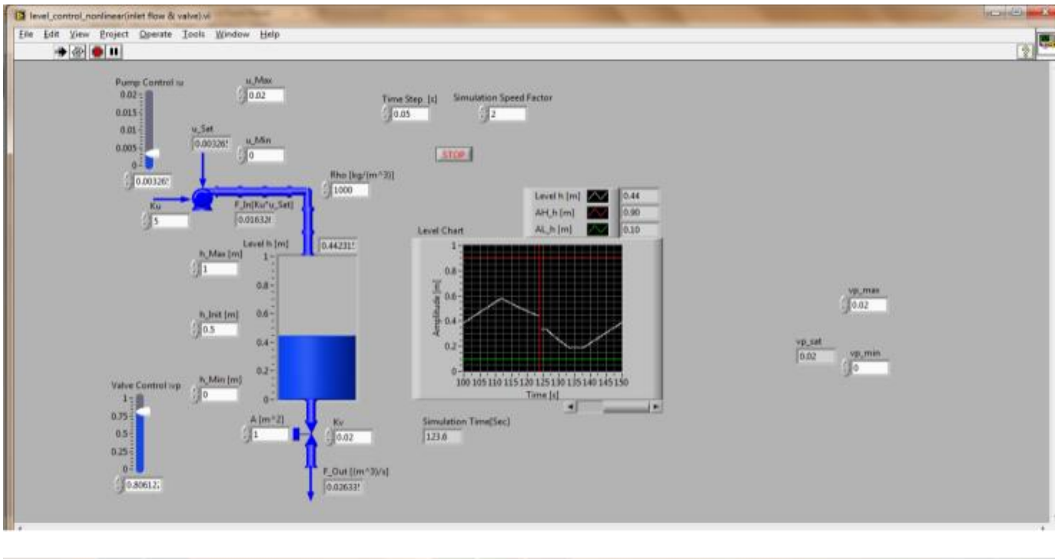


Fig. 2: Front panel of 1st order Level Control Process

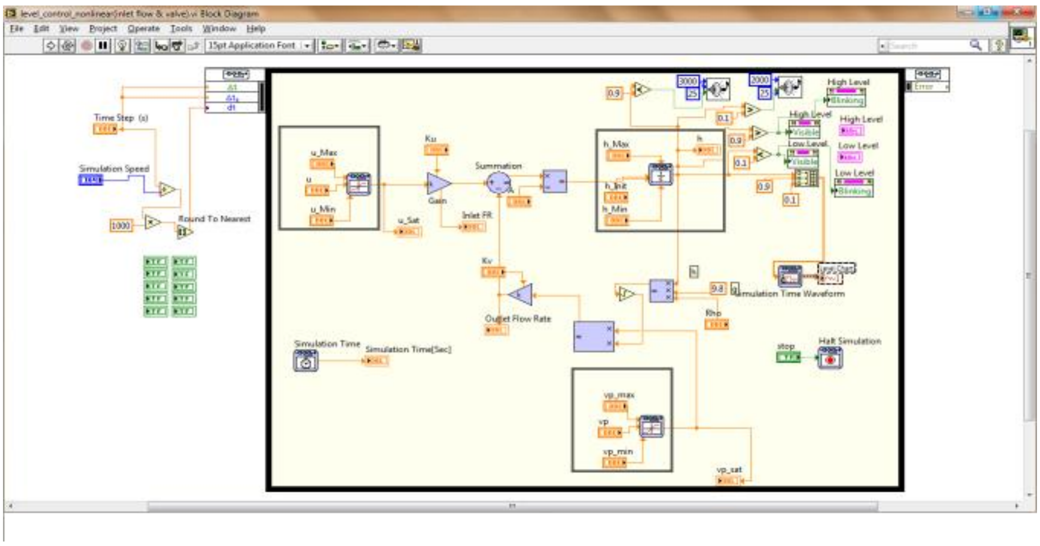
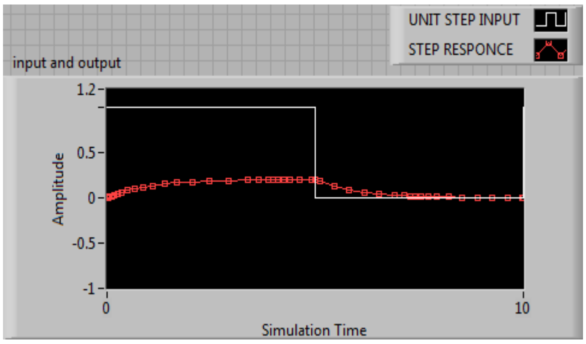


Fig. 3: Block diagram of 1st order Level Control Process

2.1.3 Results

The level of the liquid in the tank depends on the volumetric inlet liquid flow rate and valve position. These two controlled quantities **Q**i(t) and **VP**(t) are subjected to three types of forcing function i.e. step, ramp and sinusoidal each with unit amplitude and the responses of level in tank **H**(t) are shown in Fig. 4 and Fig. 5. Responses of **Q**i(t) and **VP**(t) are 180^0 out of phase with each other. The response curves of **Q**i(t) follows forcing functions with its amplitude of response i.e. K_1 depending upon Cv, ρ, G, and base value of liquid level, $\bar{h}$ in tank and valve position $\overline{vp}$, while response curves of **VP**(t) follows forcing function with amplitude K_2 which depends on base value of liquid level $\bar{h}$, and Cv, G, ρ.



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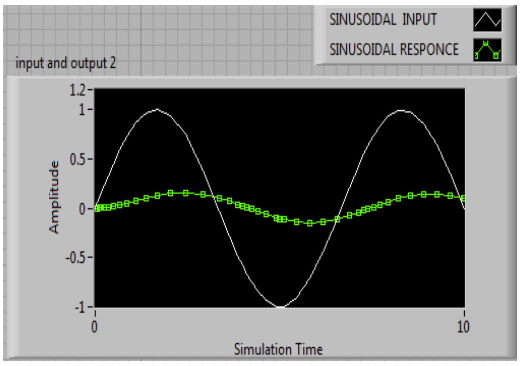

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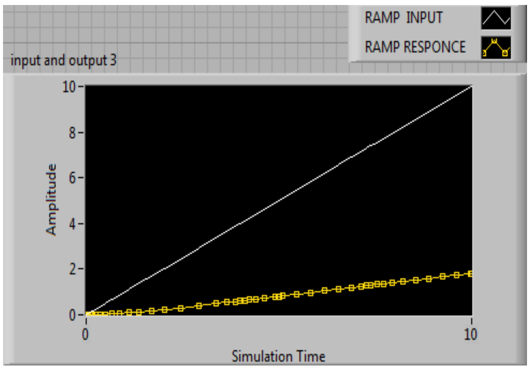
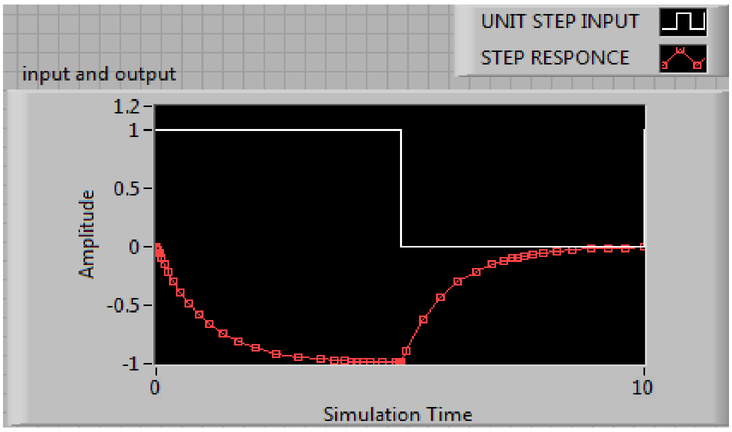
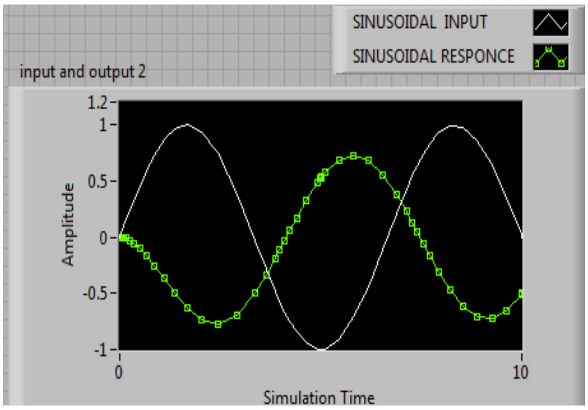


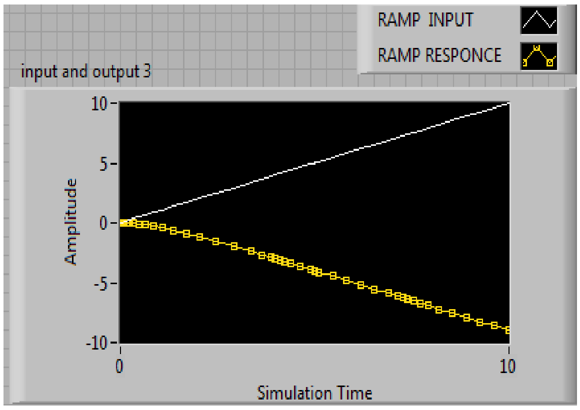
(c)

Fig. 4: Response of inlet flow [$Q_i(t)$] to (a) unit step (b) sinusoidal (b)ramp forcing function



(a)





(b) (c)

2.2 Second Order 2-Tank System (Non-Interacting system)

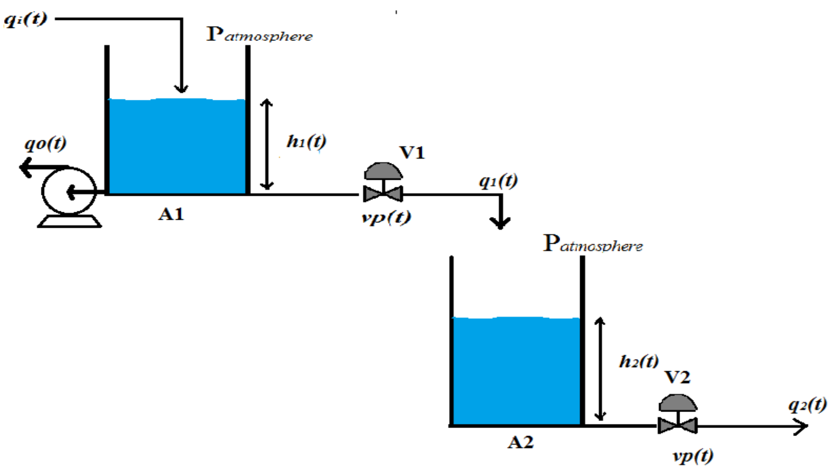


Fig. 6: Second Order (Non-Interacting) Level Process

The level process is diagrammatically explained in Fig. 6. The control objective is to maintain the level of liquid h_2 in 2nd tank. The variables are the input flow rate of liquid $q_i(t)$ and output flow rate of liquid from the 1st tank $q_0(t)$. The liquid from the 1st tank flows into the 2nd through valve V1 and ultimately the liquid exits the system from valve V2. This is a non-interacting system as the liquid level in 2nd tank depends on that of 1st tank but not vice versa i.e. it is not a 2-way flow.

2.2.1 Mathematical Modelling

Unsteady state mass balance equation for the contents of the 1st tank

$$\rho q_i(t)-\rho q_0(t)-\rho q_1(t) = \frac{dm(t)}{dt} = A_1\rho \frac{dh1(t)}{dt} \tag{7}$$

The flow $q_1(t)$ (m^3/s), through the valve V_1 is given by

$$q_1(t) = Cv_1.vp_1(t)\sqrt{\frac{\Delta P}{G}} \tag{8}$$

Unsteady mass balance equation for the contents of the 2nd tank is

$$\rho q_1(t)-\rho q_2(t) = \frac{dm(t)}{dt} = A_2\rho \frac{dh2(t)}{dt} \tag{9}$$

The flow $q_2(t)$ (m^3/s), through the valve V_2 is given by

$$q_2(t) = Cv_2.vp_2(t)\sqrt{\frac{\rho g h2(t)}{G}} \tag{10}$$

$$q_2(t) = C\acute{v}2\sqrt{h2(t)} \tag{11}$$

Eq. (7) after being linearized by Taylor series, can be written in terms of deviation variable after using the value of $q_1(t)$ from Eq. (10) and Cv from Eq. (3) as

$$\mathbf{Q}_i(t) - \mathbf{Q}_0(t) - \mathbf{Q}_1(t) = A\frac{dH1(t)}{dt} \tag{12}$$

Similarly, for second tank

$$\mathbf{Q}_1(t) - \mathbf{Q}_2(t) = A\frac{dH2(t)}{dt} \tag{13}$$

Taking the Laplace transform of (12) and (13) and rearranging the term, we get

$$\mathbf{H}_1(s) = \frac{K1}{\tau 1s+1}(\mathbf{Q}_1(t) - \mathbf{Q}_0(t)) \tag{14}$$

and,

$$\mathbf{H}_2(s) = \frac{K2}{\tau 2s+1}\mathbf{H}_1(s) \tag{15}$$

Using the value of $\mathbf{H}_1(s)$ in (15) we have,

$$\mathbf{H}_2(s) = \frac{K1.K2}{(\tau 1s+1)(\tau 2+1)}(\mathbf{Q}_1(s) - \mathbf{Q}_0(s)) \tag{16}$$

2.2.2 **Simulations**

The front panel and the block diagram associated with the implementation of the system in LabVIEW is show in Fig. 7 and Fig. 8 respectively. The front panel allows the change of both input variable $q_0(t)$ and $q_i(t)$. The system is modelled with certain such as the base value of level in either tank is 0.5m. The level of liquid in both tanks, flows out of each valve are calculated and displayed simultaneously and in real time. The plot of level v/s time is also obtained in the panel.

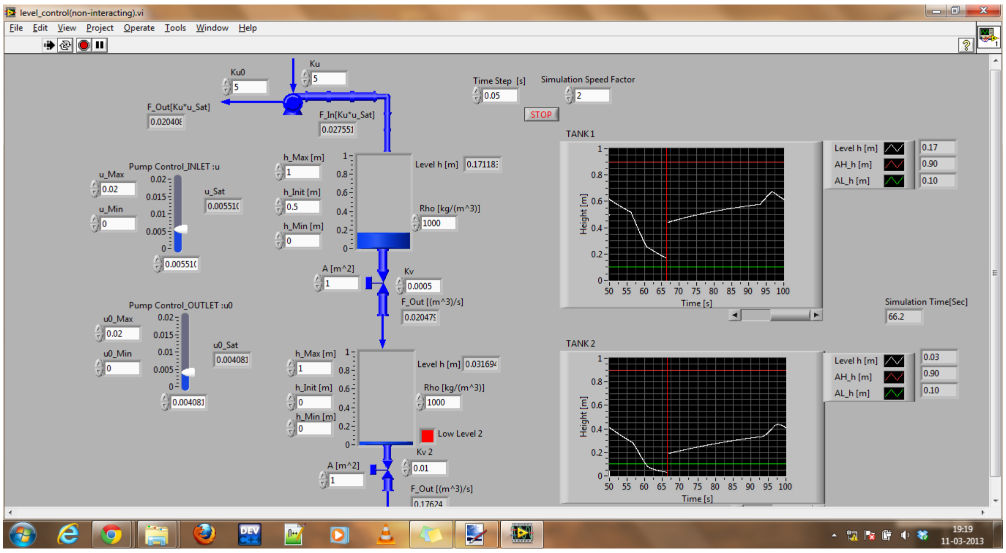


Fig. 7: Front panel of 2^{nd} order Interacting Level Control Process

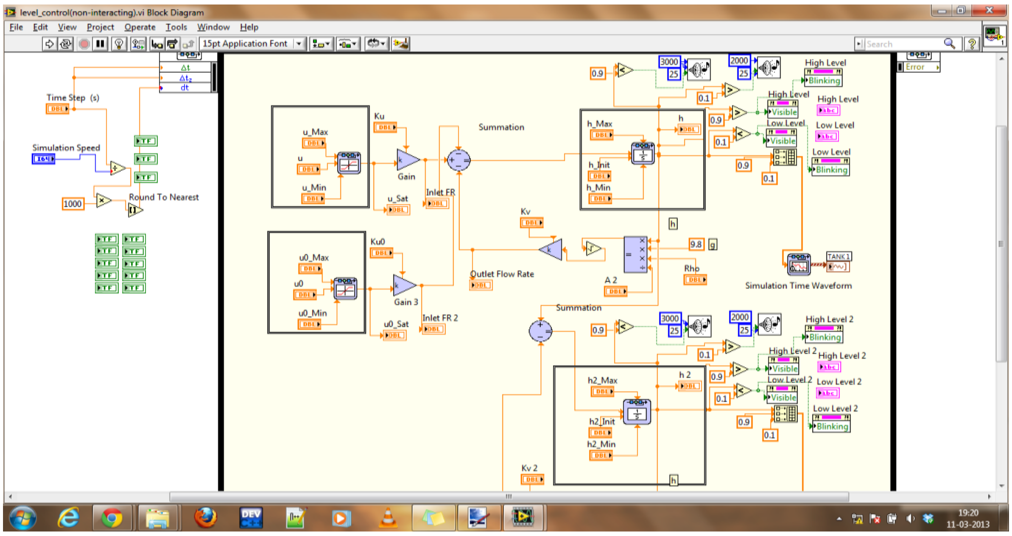
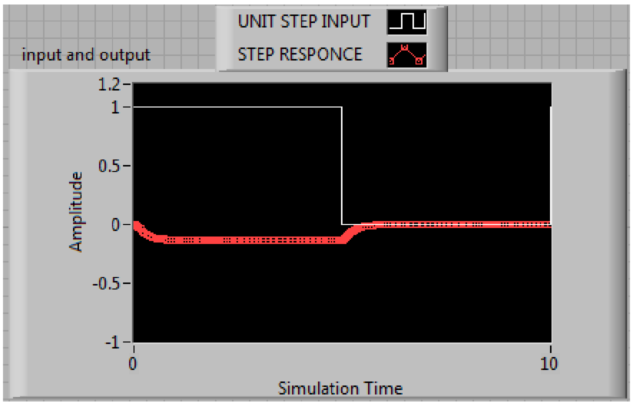


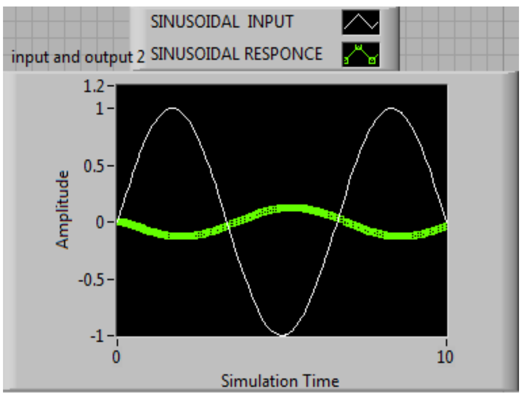
Fig. 8: Block diagram of 2^{nd} order Interacting Level Control Process

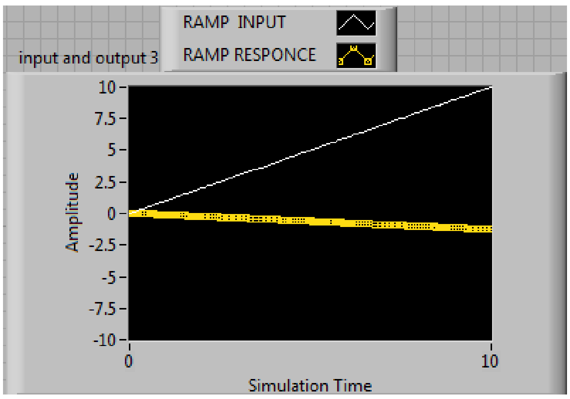
2.2.3 **Results**

This 2-tank second order non-interacting system is subjected to few forcing function such a sinusoidal, step and ramp to observe the response of the system under consideration. Due to the same denominator i.e. $(\tau_1 s+1)(\tau_2 s+1)$ we expect similar shape of response for both pump-outflow $Q_0(t)$ and input flow rate Qi(t) which is consistent with the observed response. τ1 and τ2 is related to area of cross section of tanks (A1, A2), valve coefficients (Cv1, Cv2), specific gravity of the liquid used (G), base values of the level of liquid in the tank for which the system is designed etc. So appropriate choice of the values of these parameter will give the desired effective time constant for the system. Owning to the negative sign of Q0(t) the response of the pump-outflow and input flow rate are 180^0 out of phase which is expected as per the physical situation i.e. as the input flow rate increases the level of the tank increases and decreases when the pump-outflow increases.



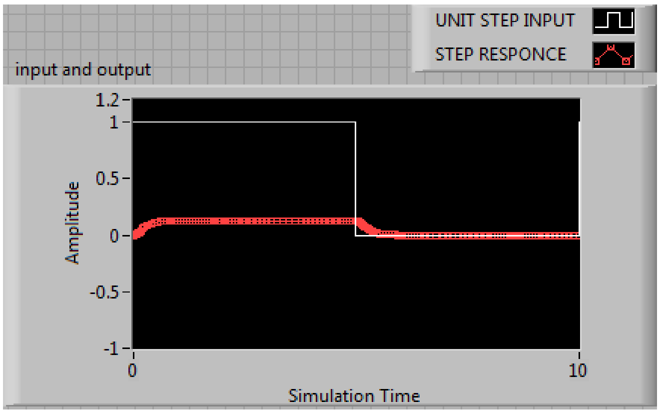
(a)



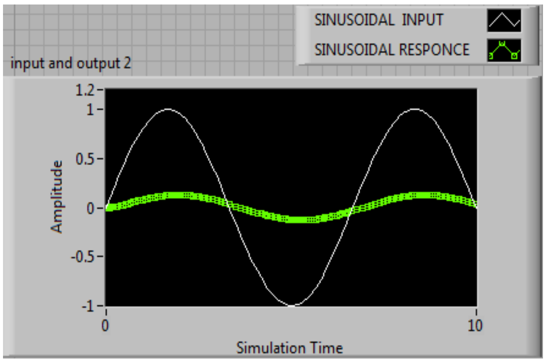


(b) (c)

Fig. 9: Response of pump-out flow [$Q_0(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function



(a)



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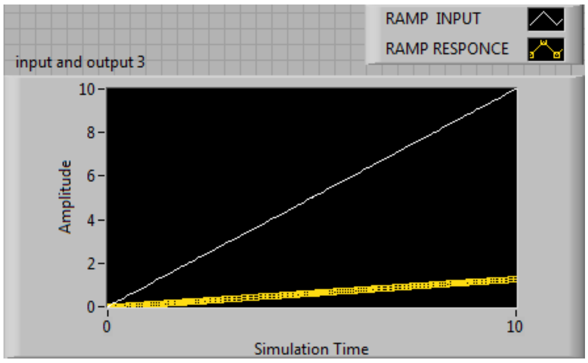


(c)

Fig. 10: Response of pump-out flow [$Q_i(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function

2.3 Second Order 2-Tank System (Interacting system)

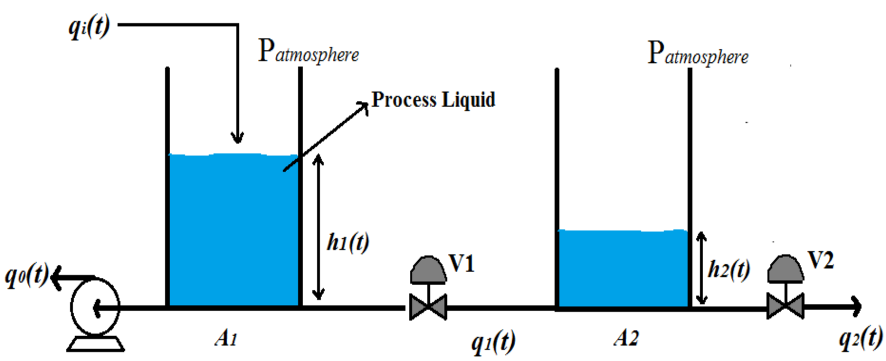


Fig. 11: Second Order (Interacting) Level Process

Interacting system, which are commonly of order higher than 1 are more frequently encountered in a process industry. A 2nd order level process has been considered here. In this process liquid flows from one tank to other through a valve V_1 and ultimately flow out of the second tank through another valve V_2. A pump with the ability to pump-in: $q_i(t)$/pump-out:$q_0(t)$ liquid in the first tank is controlled to maintain the level of liquid $h_2(t)$ in second tank. Both valves will not be controlled and be open at a particular value at all times (arbitrarily chosen as vp(t)=0.5). The flow between both tanks depends on the levels in each tanks $h_1(t)$, $h_2(t)$. The cause-and-effect relationship is a two-way path.

2.3.1 Mathematical Modelling

Unsteady state mass balance equation for the contents of the 1st tank (i.e. water) is

$$\rho q_i(t)-\rho q_0(t)-\rho q_1(t) = \frac{dm(t)}{dt} = A_1\rho\frac{dh1(t)}{dt} \quad (17)$$

The flow $q_1(t)$ (m^3/s), through the valve V_1 is given by

$$q_1(t) = Cv_1.vp_1(t)\sqrt{\frac{\Delta P}{G}} \quad (18)$$

$$q_1(t) = Cv_1.vp_1(t)\sqrt{\frac{\rho g(h1(t)-h2(t))}{G}} \quad (19)$$

$$q_1(t) = C\acute{v}1\sqrt{h1(t)-h2(t)} \quad (20)$$

Unsteady mass balance equation for the contents of the 2nd tank is

$$\rho q_1(t)-\rho q_2(t) = \frac{dm(t)}{dt} = A_2\rho\frac{dh2(t)}{dt} \quad (21)$$

The flow $q_2(t)$ (m^3/s), through the valve V_2 is given by

$$q_2(t) = Cv_2.vp_2(t)\sqrt{\frac{\rho g h2(t)}{G}} \quad (22)$$

$q_2(t) = C\acute{v}2\sqrt{h2(t)}$ (23)

Eq. (7) after being linearized by Taylor series, can be written in terms of deviation variable after using the value of $q_1(t)$ from Eq. (10) and Cv from Eq. (3) as

$\mathbf{Q}_1(t)=C_4\mathbf{H}_1(t) - C_4\mathbf{H}_2(t)$ (24)

$\mathbf{Q}_i(t)-\mathbf{Q}_0(t)-\mathbf{Q}_1(t)=A_1\frac{d\boldsymbol{H}1(t)}{dt}$ (25)

$\mathbf{Q}_i(t)-\mathbf{Q}_0(t) - C_4\mathbf{H}_1(t) + C_4\mathbf{H}_2(t) =A_1\frac{d\boldsymbol{H}1(t)}{dt}$ (26)

Taking the Laplace transform of Eq. (16) and rearranging the terms

$\mathbf{H}_1(s) = \mathbf{Q}_i(s)\frac{K4}{\tau 4s+1} + \mathbf{H}_2(s)\frac{\mathbf{1}}{\tau s+1} - \mathbf{Q}_0(s)\frac{K4}{\tau 4s+1}$ (27)

For the second tank,

$\frac{A2}{C4+C2}\frac{d\boldsymbol{H}2(t)}{dt} +\mathbf{H}_2(t) = \frac{C4}{C4+C2}\mathbf{H}_1(t)$ (28)

Taking the Laplace transform and rearranging the terms

$\mathbf{H}_2(s)=\mathbf{H}_1(s)\frac{K5}{\tau 5+1}$ (29)

Substituting the value of $\mathbf{H}_1(s)$ in Eq. (19)

$\mathbf{H}_2(s)=\mathbf{Q}_i(s)\frac{K4.K5/(1-K5)}{\left(\frac{\tau 4.\tau 5}{1-K5}\right)s^2+\left(\frac{\tau 4.+\tau 5}{1-K5}\right)s+1} +$

$\mathbf{Q}_0(s)\frac{-K4.K5/(1-K5)}{\left(\frac{\tau 4.\tau 5}{1-K5}\right)s^2+\left(\frac{\tau 4.+\tau 5}{1-K5}\right)s+1}$ (30)

After substituting the values we get

$\mathbf{H}_2(s)=\mathbf{Q}_i(s)\frac{6.5856}{70.2967s^2+23.844s+1}+ \mathbf{Q}_0(s)\frac{-6.5856}{70.2967s^2+23.844s+1}$ (31)

2.3.2 **Simulations**

Interacting 2nd order level process has been modelled and simulated. The block diagram and front panel are shown in Fig. 7 and Fig. 8 respectively. As the flow $q_i(t)$ *and* $q_0(t)$ are changed, the level in the first tank $h_1(t)$ changes which in turn changes the level in second tank $h_2(t)$. Level of both these tanks are plotted against the time as the controlled variables $q_i(t)$ and $q_0(t)$ are varied and shown in the front panel.

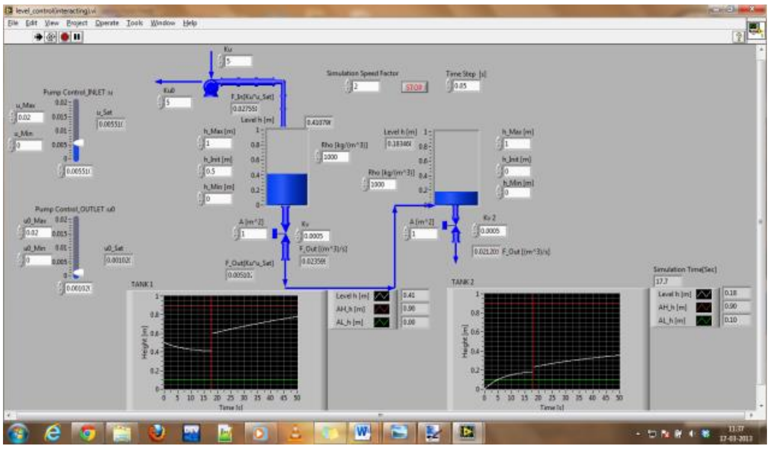


Fig. 12: Front panel of 2nd order Interacting Level Control Process

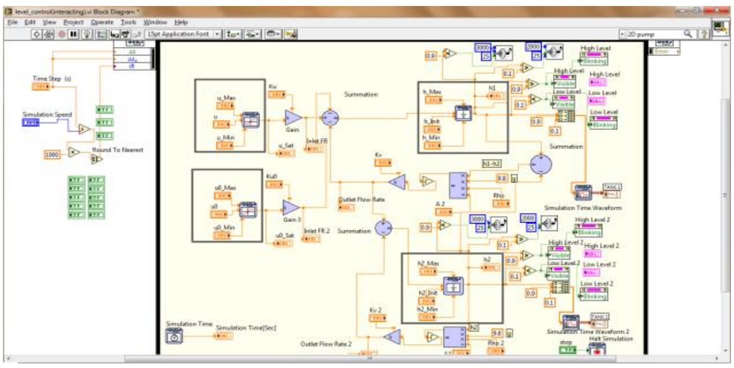
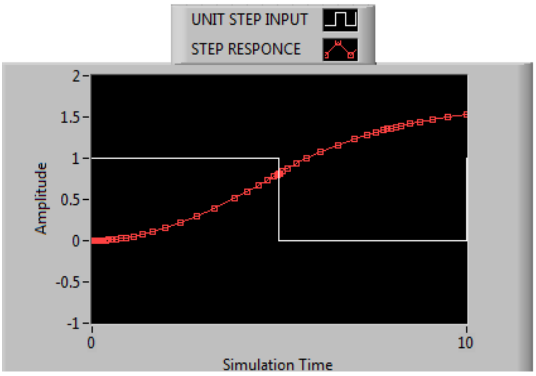


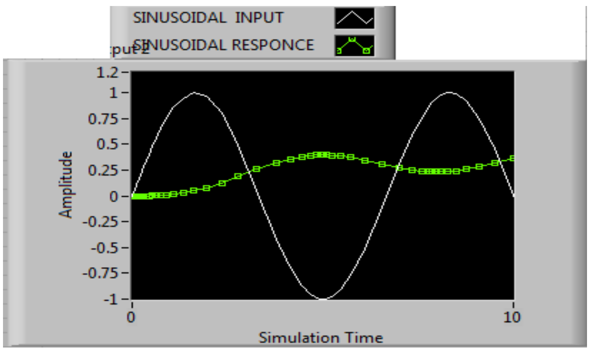
Fig. 13: Block diagram of 2nd order Interacting Level Control Process

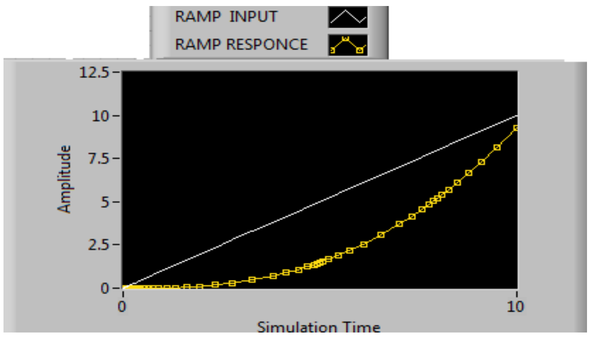
2.3.3 **Results**

The level of the liquid in the second tank depends on the volumetric pump-in and pump-out liquid flow rates. These two controlled quantities **Q**i(t) and $\mathbf{Q_0}$(t) are subjected to three types of forcing function i.e. step, ramp and sinusoidal each with unit amplitude and the responses of level in desired tank **H**$_2$(t) are show in Fig. 9 and Fig. 10. Responses of **Q**i(t) and **Q**$_0$(t) are 180^0 out of phase. The response curves of **Q**i(t) and **Q**$_0$(t) does not exactly follow forcing functions. The desired gain is obtained by taking appropriate values of K_4 and K_5. Unlike in first order non-interacting system, there is no one time constant τ i.e. it cannot be said that any one of the τ values in second (or higher) order system represents the time to reach 63.2% of total change. However, τ values are indicative to the dynamics of the system, slower system have larger τ values and vice-versa.



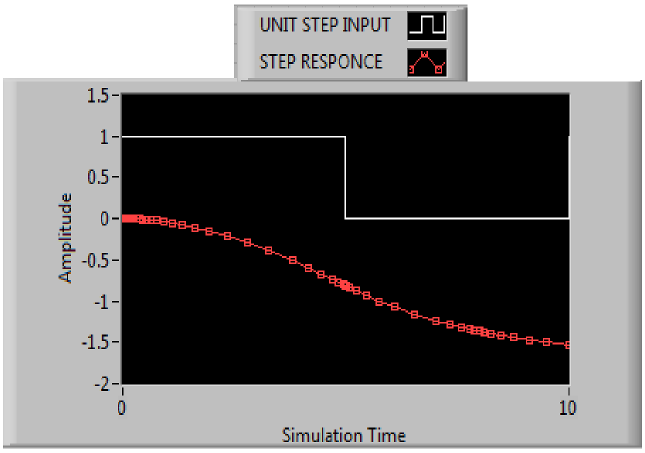
(a)



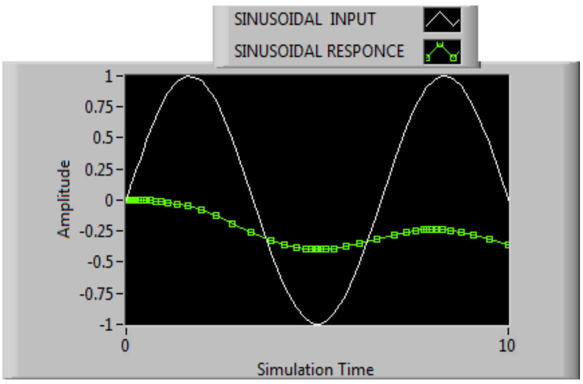


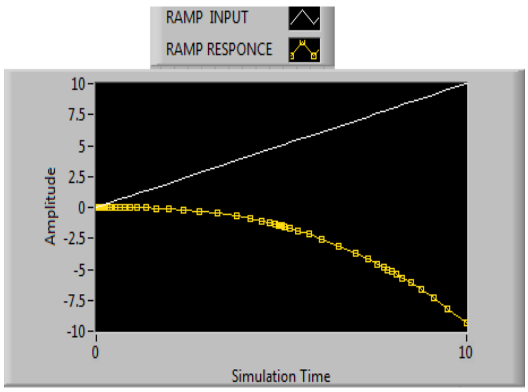
(b) (c)

Fig. 14: Response of pump-out flow [$Q_i(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function



(a)





(b) (c)

Fig. 15: Response of pump-out flow [$Q_o(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function

2.4 Third Order 3-Tank System (Non-Interacting system)

This is system is an extension of the 2-tank Non-Interacting system discussed in section 2.2 with another tank in series with the previous two. The control objective remains similar, maintaining the level of the liquid in 3rd tank by controlling the input flow rate and the pump out flow from the 1st tank. Clearly, this system is a non-interacting system as level of liquid in a tank depends on the level of liquid in the tank(s) above it in the series but not vive-versa.

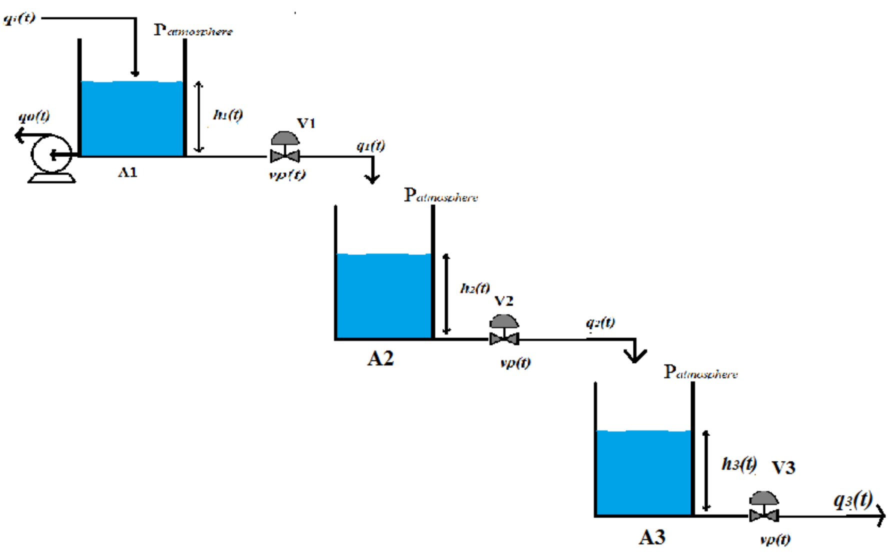


Fig.16: Third Order (Non-Interacting) Level Process

2.4.1 Mathematical Modelling

The mass balance equation of the first two tanks remains same as section 2.2 (2-tank non-interacting system). Unsteady state mass balance equation for the contents of the 3rd tank:

$$\rho q_2(t)-\rho q_3(t) = \frac{dm(t)}{dt} = A\rho\,\frac{dh(t)}{dt} \tag{32}$$

The flow through the valve V3, q_3 (m^3/s) is given by

$$q_3(t) = Cv_3.vp_3(t)\sqrt{\frac{\Delta P}{G}} \tag{33}$$

Eq. (1) after being linearized by using Taylor series can be written in terms of deviation variable after using the value of $q_0(t)$ from Eq. (2) and Cv from Eq. (3) as

$$C_2\mathbf{Q}_2(t) - C_3\mathbf{Q}_3(t) = A_3\frac{\boldsymbol{dh3}(t)}{dt} \tag{34}$$

Taking the Laplace Transform and re-arranging the term with appropriate substitution

$$\mathbf{H}_3(s) = \frac{K3}{\tau 3+1}\,\mathbf{H}_2(s) \tag{35}$$

Substituting the expression of $\mathbf{H}_2(s)$

$$\mathbf{H}_3(s) = \frac{K1.K2.K3}{(\tau 1s+1)(\tau 2s+1)(\tau 3s+1)} (\mathbf{Q}_i(s) - \mathbf{Q}_0) \tag{36}$$

2.4.2 Simulations

This system is implemented in LabVIEW and the front panel (Fig. 17) is developed by the block diagram as show in Fig. 18. The front panel provides the capability to change the inputs as desired. The level in different tanks and the flow through the different valves are continuously calculated and displayed along with the corresponding plots. Also the programming is done to give additional capability to the front panel to change the Cv, Cp, ρ, A at will to make it capable for usage with any liquid or tank dimensions.

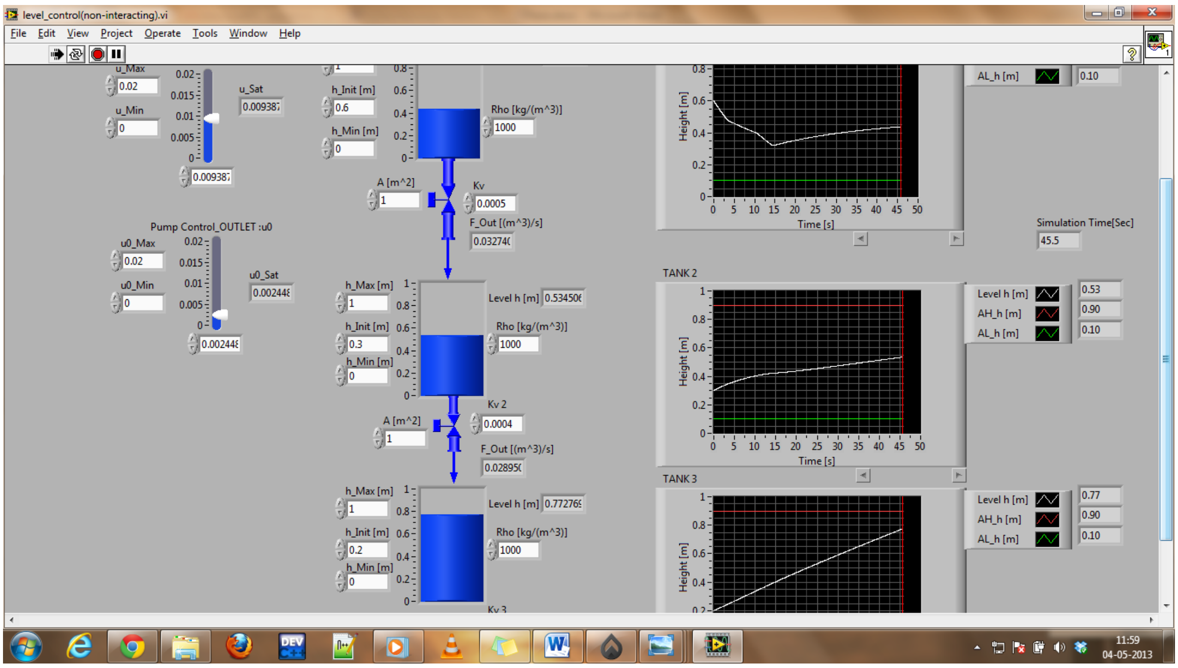


Fig. 17: Front panel of 3rd order Non-Interacting Level Control Process

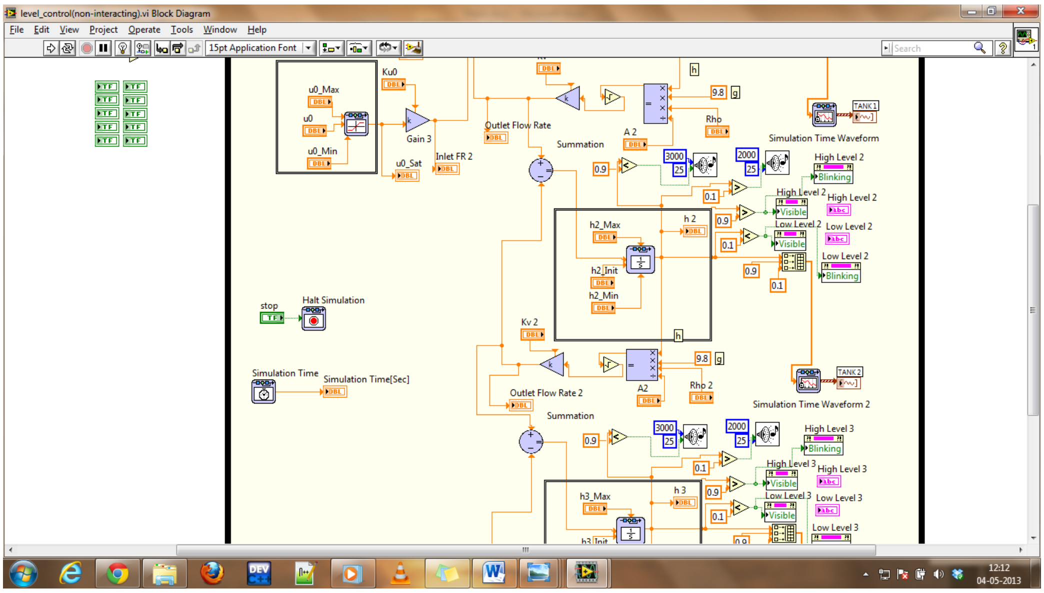
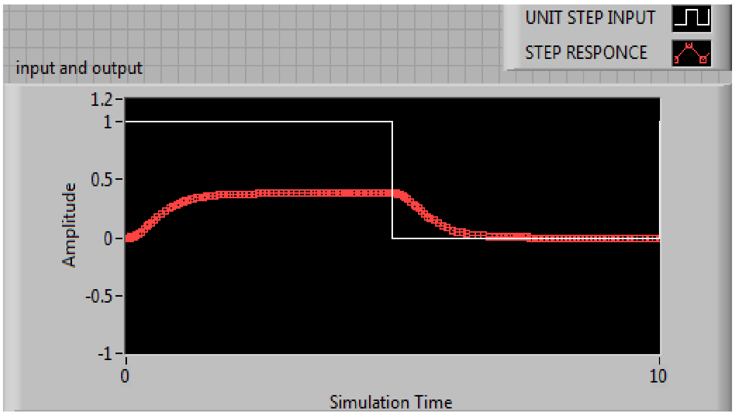


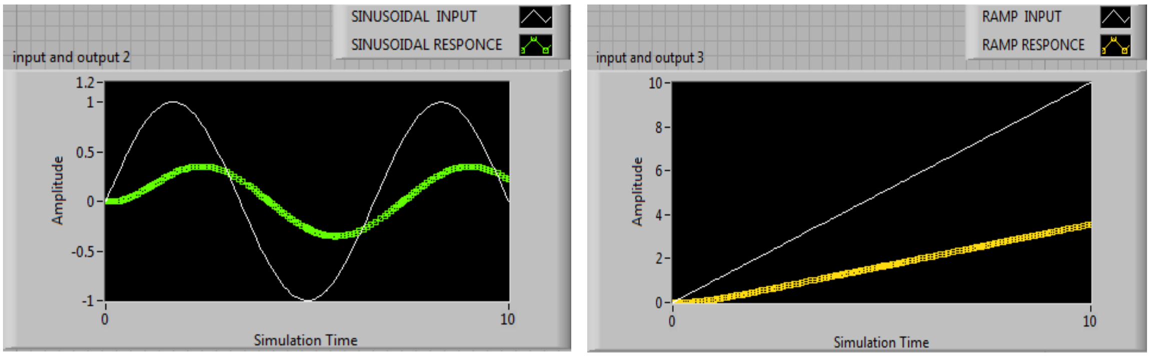
Fig. 18: Block diagram of 3rd order Non-Interacting Level Control Process

2.4.3 Results

The controlled quantities Qi(t) and $Q_0(t)$ are subjected to common forcing functions and the response of the system is observed. A finite dead-time is observed when the output response tries to follow the input function as observed in the results Fig.19 and Fig. 20. The amplitude and the effective time constant of the system depends on cross section of tanks (A1, A2), valve coefficients (Cv1, Cv2), specific gravity of the liquid used (G), base values of the level of liquid in the tank for which the system is designed etc. so appropriate selection of the values can be made depending how the transient response is desired. The expected 180^0 phase difference between the response of $Q_i(t)$ and Q_0 is observed. The exact transfer function is calculated by substituting the values of parameters and assuming others (such as the base value of the height of the tank, which is decided while the system is designed).

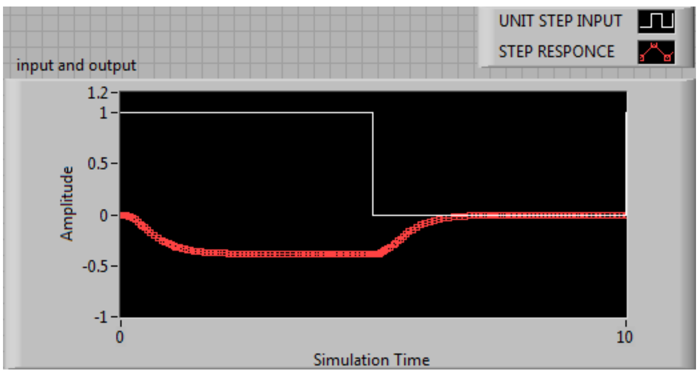


(a)

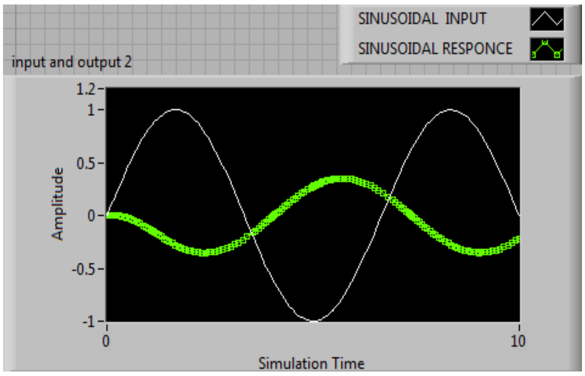


(b) (c)

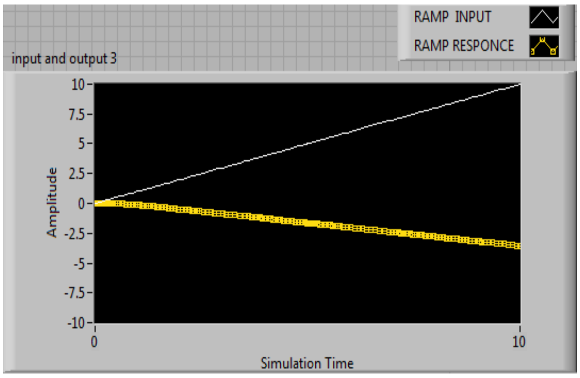
Fig. 19: Response of pump-out flow [$Q_i(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function



(a)



(b)



(c)

Fig. 20: Response of pump-out flow [$Q_0(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function

CHAPTER-3

THERMAL PROCESS

This chapter elaborates on the two most commonly encountered thermal process; Adiabatic and Non-Adiabatic. The control objective remains maintaining the liquid at a desired temperature such as in heat exchanger system. Each of these two processes has been mathematical modelled from the energy balance equation and other consideration before being implemented in LabVIEW. This follows the response generation by the systems to different forcing function.

3.1 Adiabatic First Order Thermal Process

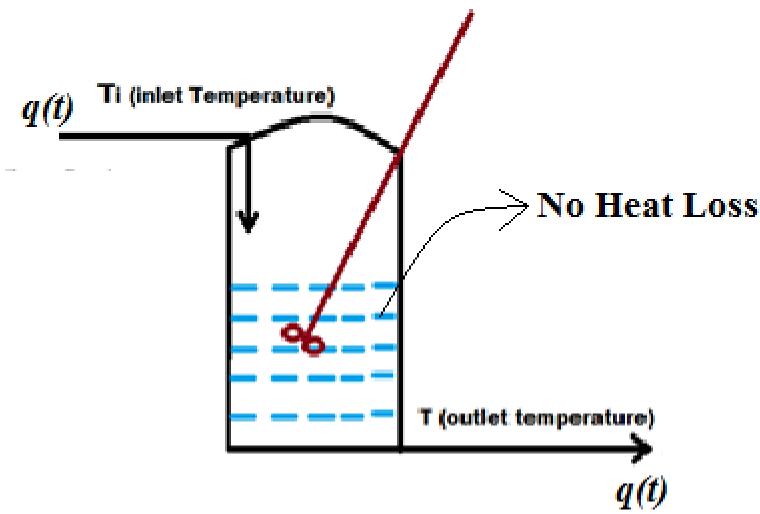


Fig.21: First Order Adiabatic Thermal Process

Where,

ρ_i, ρ = Inlet and outlet Liquid densities [kg/m^3]

Cp_i, Cp = Inlet and Outlet heat capacities at constant pressure [J/kg ^{0}C]

Cv = Heat capacities at constant volume

V = Volume of Tank [m^3]

h_i, h = Inlet and outlet Liquid Enthalpy

q(t) = Constant Inlet Volumetric flow of processes liquid

The process fluid flows in with the rate of q(t) and flows out with the same rate. It has a temperature of T_i(t) when it enters the system which becomes T(t) when it leaves the system. The mathematical modelling and analysis of process is done assuming this is an Adiabatic Process i.e. there is no heat loss to surrounding environment. Certain assumptions made in this thermal system are that liquid densities and heat capacities of inlet and outlet flow is constant (in practise they are both function of temperature) and the tank is well insulated.

3.1.1 Mathematical Modelling

Unsteady energy balance equation for the contents of the tank

$$q\rho_i h_i(t) - q\rho h(t) = \frac{d[V\rho u(t)]}{dt} \tag{1}$$

$$q\rho_i Cp_i T_i(t) - q\rho Cp T(t) = \frac{d[V\rho Cv T(t)]}{dt} \tag{2}$$

Since, it is assumed $\rho = \rho_{i,}$ $Cp = Cp_i$ we have (3)

$$q\rho Cp T_i(t) - q\rho Cp T(t) = \frac{d[V\rho Cv T(t)]}{dt} \tag{4}$$

In terms of deviation variable the above eq. can be re-written as,

$$q\rho Cp \mathbf{T}_i(t) - q\rho Cp \mathbf{T}(t) = \frac{d[V\rho Cv \boldsymbol{T}(t)]}{dt} \tag{5}$$

$$\frac{V\rho Cv}{q\rho Cp}\frac{d\,\boldsymbol{T}(t)}{dt} + \mathbf{T}(t) = \mathbf{T_i(t)} \tag{6}$$

Due, to the linear nature of the equation linearization is not required. Taking the Laplace Transform and rearranging the terms,

$$\mathbf{T}(t) = \mathbf{T}_i(s)\,\frac{1}{\tau s+1} \tag{7}$$

Where, $\tau = \frac{Cv.V}{q.Cp}$

3.1.2 Simulations

The front panel of this system is programmed and implemented in LabVIEW Fig. 22 and Fig. 23. The control knobs provides the ability to change the input flow rate of liquid q(t) and input temperature of process liquid Ti(t) in order to maintain the temperature of the process fluid flowing out T(t). Real time calculation of the T(t) is displayed and plotted. As the input and output flow rate of liquid is same the level of liquid in the tank remains same at all time.

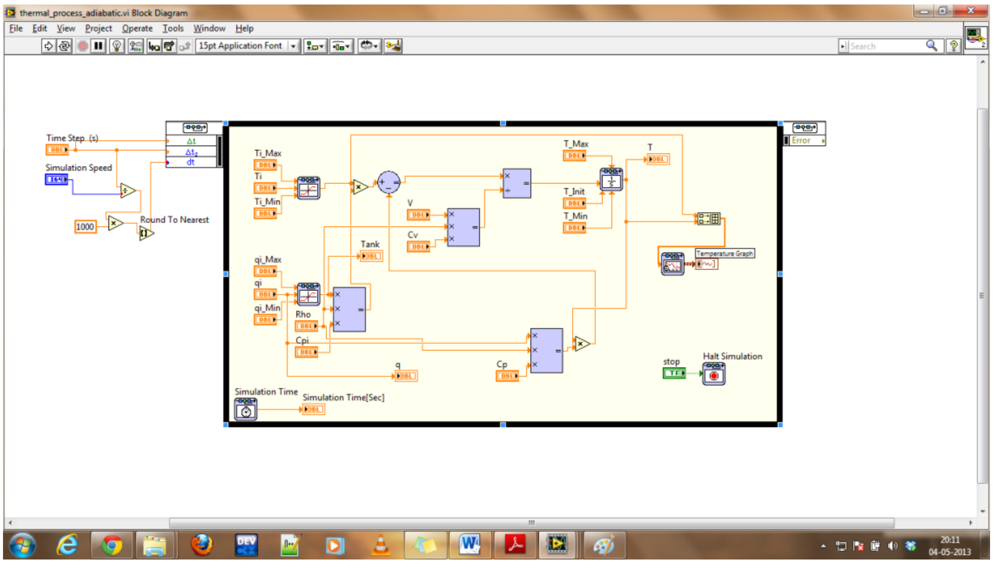


Fig. 22: Block diagram of 1st order Adiabatic Thermal Process

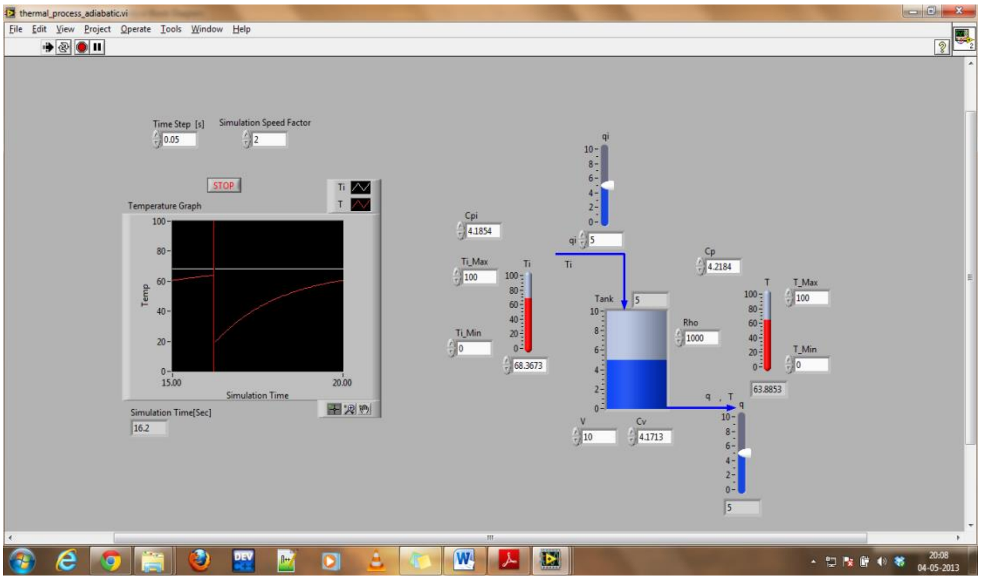
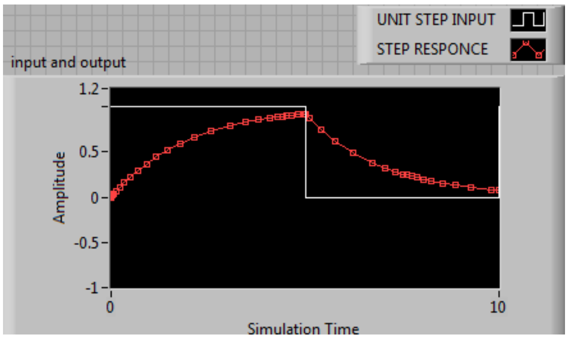


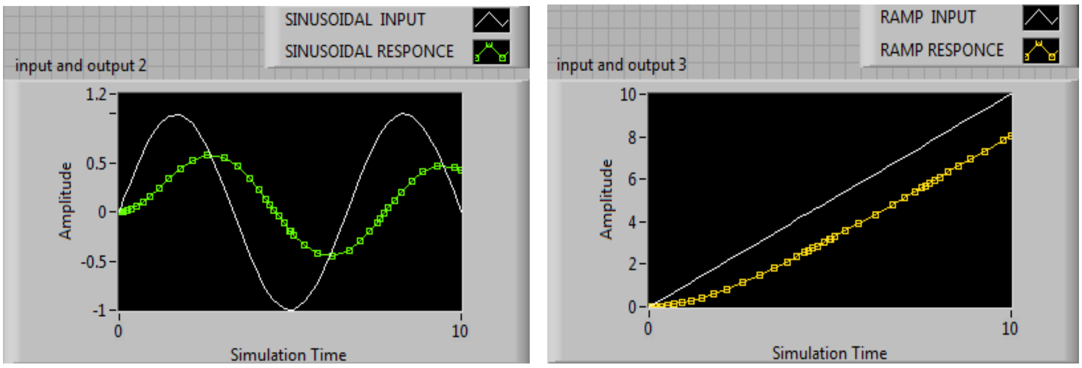
Fig. 23: Front Panel of 1st order Adiabatic Thermal Process

3.1.3 Results

As expected form the 1st order expression obtained in Eq. (7), the output response of the forcing function follows the input curves faithfully where the time constant, τ depends on parameters Cv, V, q and Cp. The transfer function used to generate the responses is obtained by putting the numerical values of the parameters.



(a)



(b) (c)

Fig. 24: Response of input temperature of Process Liquid [Ti(t)] to (a) unit step (b) sinusoidal (c) ramp forcing function

3.2 Non-Adiabatic First Order Thermal Process

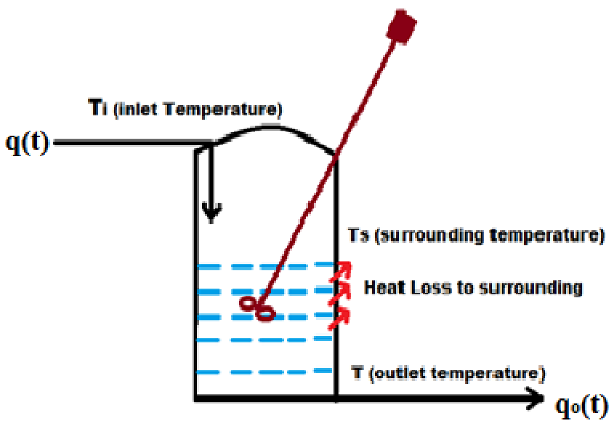


Fig.25: First Order Non-Adiabatic Thermal Process

Where,

Ts = Surrounding Temperature [^{0}C]

A = Heat Transfer Area [m^2]

U = Overall Heat Transfer Coefficient

The process and the control objective remains the same. Main and only difference of this system with the one discussed in previous section, is that the assumption of tank being fully insulated is done away with. The surrounding temperature, $T_s(t)$ thus now becomes a disturbance and is taken into account in the energy balance equation.

3.2.1 Mathematical Modelling

Unsteady energy balance equation for the contents of the tank

$$q\rho_i h_i(t) - q\rho h(t) - Q(t) = \frac{d[V\rho u(t)]}{dt} \tag{8}$$

$$q\rho_i h_i(t) - q\rho h(t) - UA[T(t) - Ts(t)] = \frac{d[V\rho CvT(t)]}{dt} \tag{9}$$

In terms of deviation variable the above eq. can be re-written as,

$$q\rho Cp\mathbf{T}_i(t) - q\rho Cp\mathbf{T}(t) - UA[\mathbf{T}(t) - \mathbf{T}s(t)] = \frac{d[V\rho Cv\boldsymbol{T}(t)]}{dt} \tag{10}$$

Which can be re-arranged and written as,

$$\frac{V\rho Cv\boldsymbol{T}(t)]}{\mathrm{q\rho Cp+UA}}\frac{d\boldsymbol{T}(s)}{dt} + \mathbf{T}(t) = \frac{\mathrm{q\rho Cp}}{\mathrm{q\rho Cp+UA}}\mathbf{T}_i(t) + \frac{\mathrm{UA}}{\mathrm{q\rho Cp+UA}}\mathbf{T}s(t) \tag{11}$$

Absence of non-linear terms removes the need of linearization. Taking the Laplace transform,

$$\tau s\mathbf{T}(s) + \mathbf{T}(s) = K_1\mathbf{T}_i(s) + K_2\mathbf{T}_s(s) \tag{12}$$

$$\text{where, } \tau = \frac{\mathrm{V\rho Cv}}{q\rho Cp+UA} \quad K_1 = \frac{q\rho Cp}{q\rho Cp+UA} \quad K_2 = \frac{UA}{q\rho Cp+UA} \tag{13}$$

$$\mathbf{T}(s) = \frac{K1}{\tau s+1}\mathbf{T}_i(s) + \frac{K2}{\tau s+1}\mathbf{T}_s(s) \tag{14}$$

3.2.2 Simulations

The implementation of this process is similar to the previous and is shown in Fig. 26 and Fig. 27. Apart from the regular control knobs an additional control is provided to take into account the temperature of the surrounding. For simulations purpose this is a manual control while for practical implementation this can be a temperature sensor followed by a signal conditioning circuit. T(t) is plotted as Ts(t) and Ti(t) is varied.

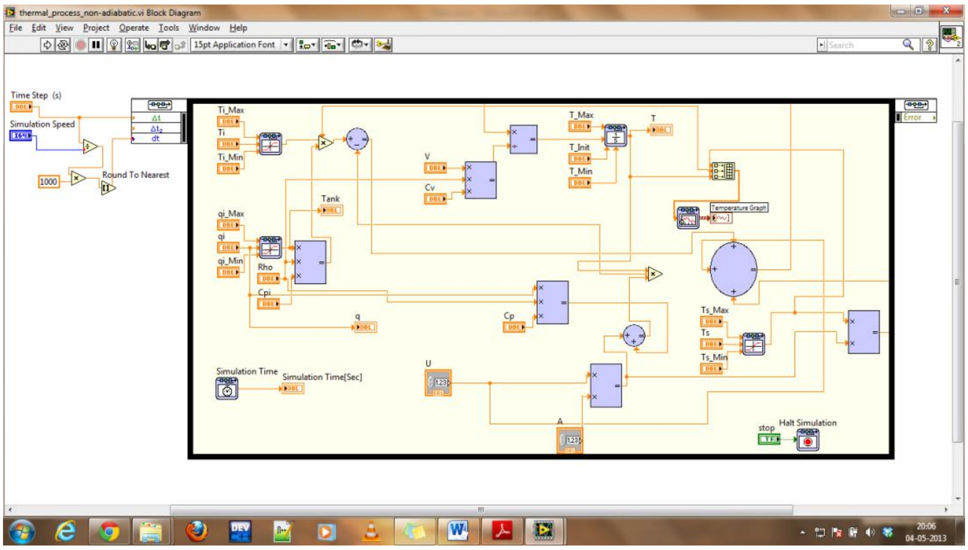


Fig. 26: Block diagram of 1st order Non-Adiabatic Thermal Process

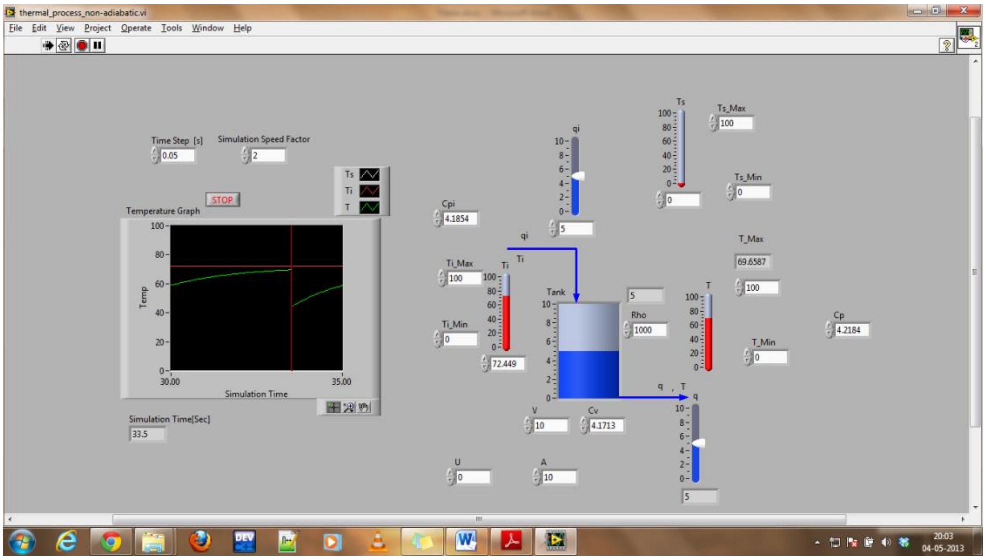
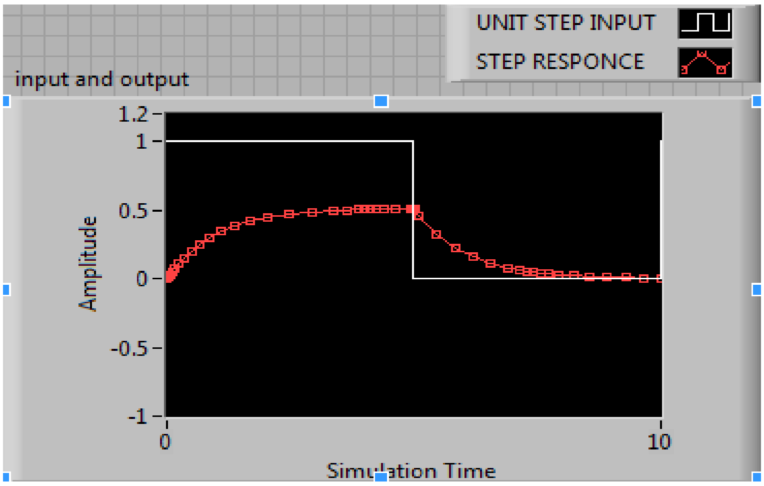


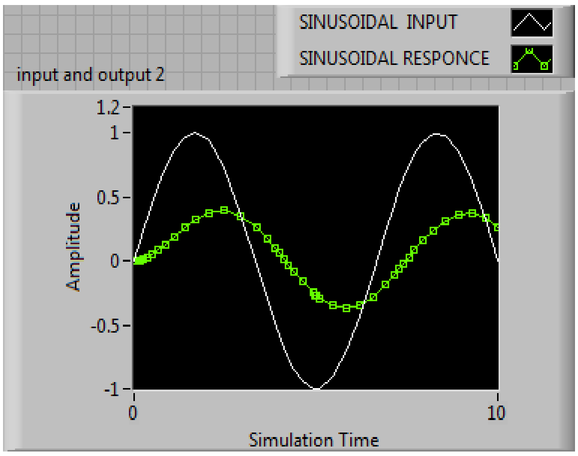
Fig. 27: Front Panel of 1st order Non-Adiabatic Thermal Process

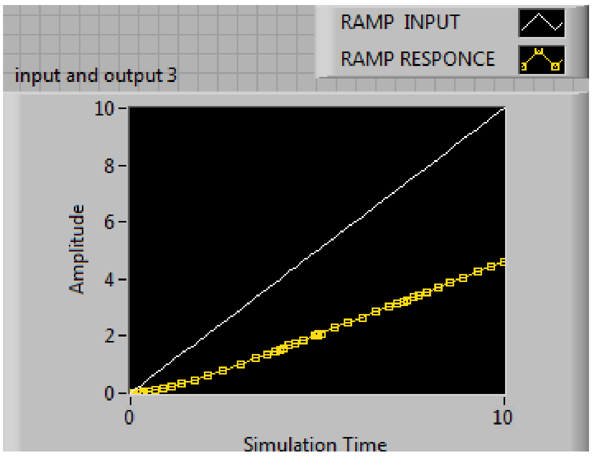
3.2.3 Results

The responses obtained for both surrounding temperature, Ts and Ti as disturbance is same other than the amplitude as expected from Eq. (14) The parameters on which K_1, K $_a$ and τ depends are explicitly mentioned in Eq. (13) They can changed as per the response required. Clearly, the system is first order and the shape of output response curves is as expected. The finite phase difference is evident in the sinusoidal response Fig. 27 (b) as is the time constant in Fig. 28(c).



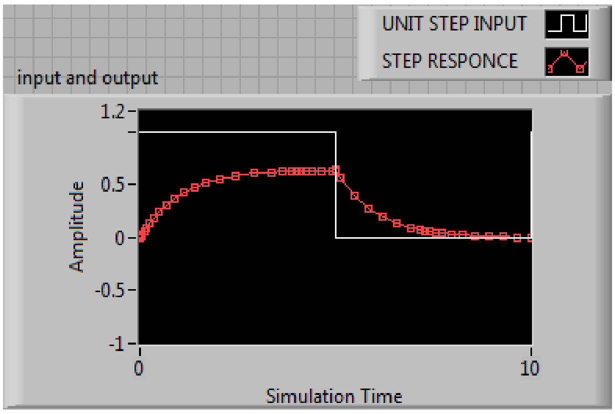
(a)



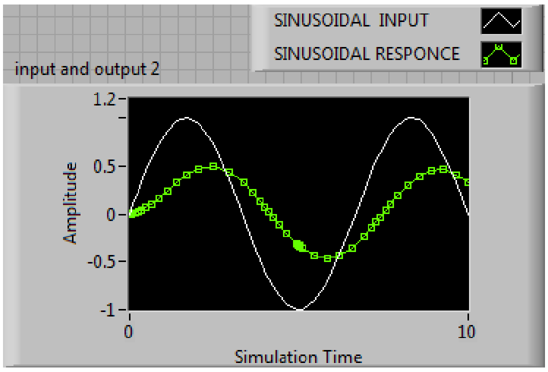


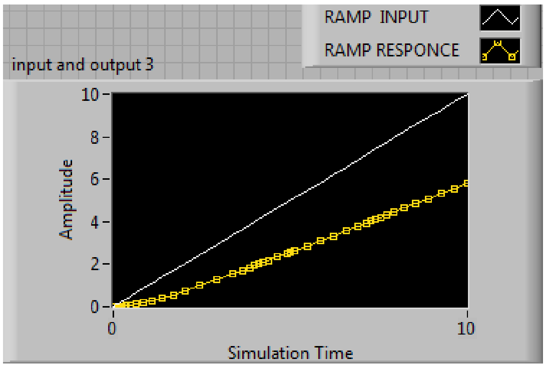
(b) (c)

Fig. 28: Response of input temperature of Process Liquid [Ti(t)] to (a) unit step (b) sinusoidal (c) ramp forcing function



(a)





(b) (c)

Fig.29 Response of Surrounding Temperature [Ts(t)] to (a) unit step (b) sinusoidal (c) ramp forcing function

CHAPTER-4

GAS PROCESS

4.1 First Order Gas Process

Gas Process is another very widely encountered process and so the analysis of the process after its implementation is one of interest. The control objective, mathematical modelling, followed by its implementation and response to input forcing functions are elaborately explained in the subsequent sections.

4.1 First Order Gas Process

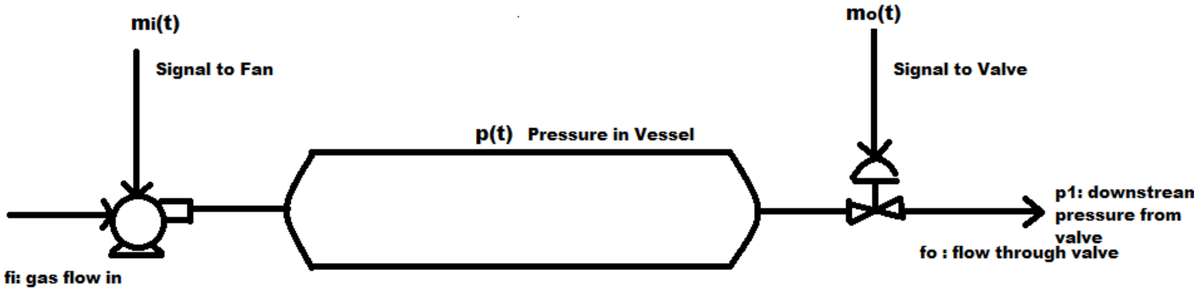


Fig.30 First Order Gas Process

Consider the tank show in Fig. 29. A fan blows air into it, and from the tank the air flows out through the valve. In order to assist in the mathematical modelling let the air flow delivered by the fan be given by

$$f_i(t) = 0.16m_i(t)$$

where,

$f_i(t)$ = gas flow in scf/min, where scf is cubic feet at standard condition of 60^0F and 1atm

$m_i(t)$ = signal to fan, %

The flow through the valve is expressed by

$$f_o(t) = 0.00506m_0(t)\sqrt{p(t)[p(t) - p1(t)]}$$

where,

$f_0(t)$ = gas flow, scf/min

$m_0(t)$ = signal to valve, %

$p(t)$ = pressure in tank, psia

$p_1(t)$ = downstream pressure from valve, psia

The volume of tank, V = 20 ft^3 and the assumption is made that the process occurs isothermally at 60^0 F. Also let the steady state conditions are:

$\overline{f\iota} = \overline{f0}$ = 8 scfm; $\bar{p}$ = 40 psia; $\overline{p1}$ = 1 atm; $\overline{m0} = \bar{m}$i = 50%

4.1.1 Mathematical Modelling

Unsteady state mole balance around the control volume

$$\bar{\rho}f_i(t) - \bar{\rho}f_0(t) = \frac{dn(t)}{dt} \quad (1)$$

where,

$\bar{\rho}$ = molal density of a gas at standard conditions, 0.00263 lbmoles/scf

$n(t)$ = moles of gas in tank, lbmoles

Fan provides another equation,

$$f_i(t) = 0.16m_i(t) \quad (2)$$

The valve provides still another equation,

$$f_o(t) = 0.00506m_0(t)\sqrt{p(t)[p(t) - p1(t)]} \quad (3)$$

Because the pressure in the tank is low, ideal gas equation of state can be used to relate the moles in the tank to the pressure.

$$p(t)V = n(t)RT \quad (4)$$

In terms of deviation variable,

$$\bar{\rho}\mathbf{F}_i(t) - \bar{\rho}\mathbf{F}_0(t) = \frac{V}{RT}\frac{d\,\boldsymbol{P}(t)}{dt} \tag{5}$$

writing the steady state equation of fan

$\mathbf{F}_i(t) = 0.16\mathbf{M}_i(t)$ and using it in Eq. (5) we have,

$$\mathbf{F}_0(t) = C_1\mathbf{M}_0(t) + C_2\mathbf{P}(t) + C_3\mathbf{P}_1(t) \tag{6}$$

where, $C_1 = 0.00506\sqrt{\bar{p}(\bar{p} - \overline{p1})}$

$C_2 = 0.00506m_0(1/2)\,[\bar{p}(\bar{p} - \overline{p1})]^{-1/2}(2\bar{p} - \overline{p1})$

$C_3 = 0.00506m_0(1/2)\,[\bar{p}(\bar{p} - \overline{p1})]^{-1/2}(-\bar{p})$

Taking the Laplace transform and rearranging the term we have

$$P(s) = \frac{K1}{\tau+1}\mathbf{M}_i(s) - \frac{K2}{\tau+1}\mathbf{M}_0(s) - \frac{K3}{\tau+1}\mathbf{P}_1(s) \tag{7}$$

Because the steady state values and other process information are known, the values of the constants can be calculated.

$K_1 = 0.615\,\frac{psi}{\%}$; $K_2 = 0.619\frac{psi}{\%}$; $K_3 = -0.611\frac{psi}{\%}$; $\tau = 5.242$ min

4.1.2 Simulations

The implementation of First Order Gas process in LabVIEW is show in Fig. 31 and Fig. 32. Control knobs for $m_i(t)$, signal to fan; $m_0(t)$, signal to valve and $p_1(t)$, downstream pressure from valve are provided. The pressure gauge gives the pressure in the vessel visually which is being calculated by continuously and plotted against time. The simulation speed factor is adjusted so is the various gains associated with the system.

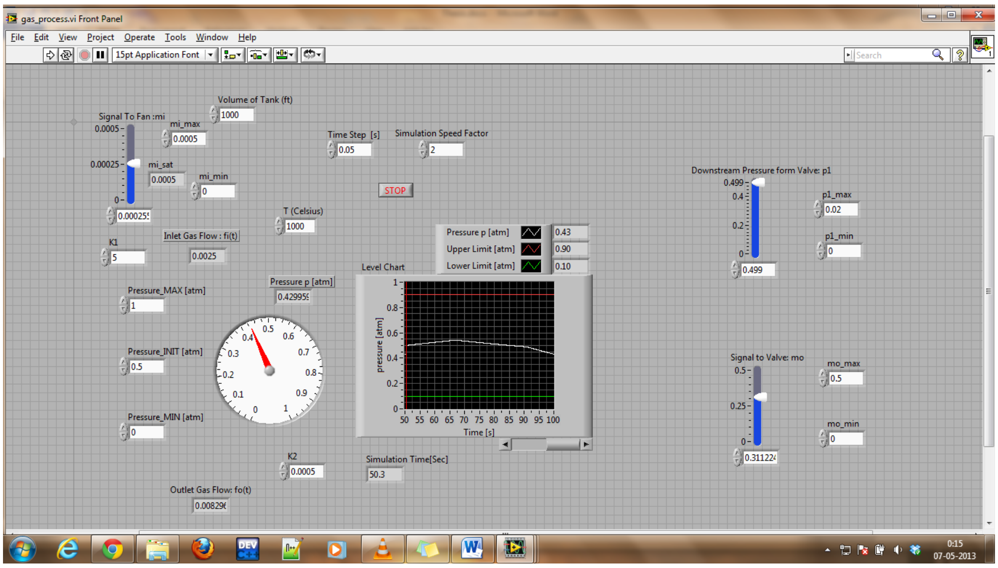


Fig. 31 First Order Gas Process Front Panel

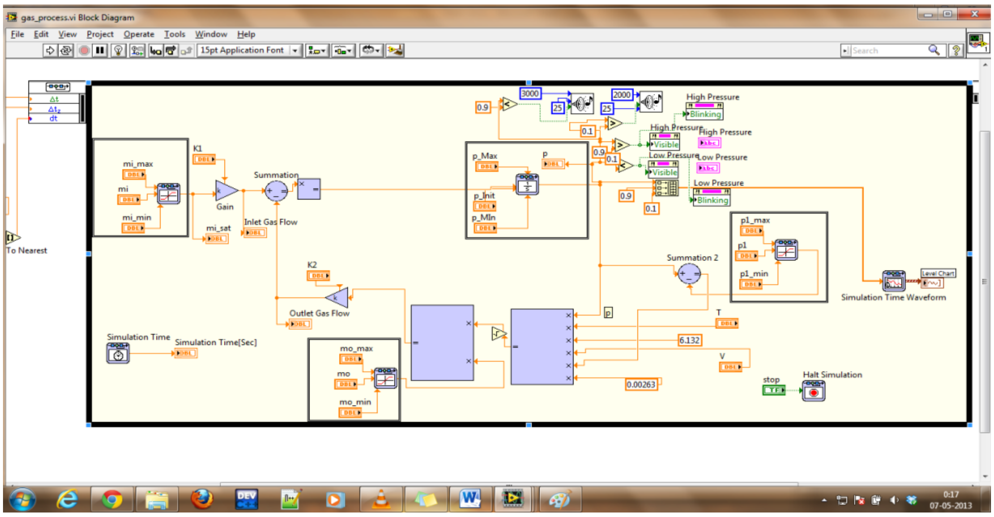
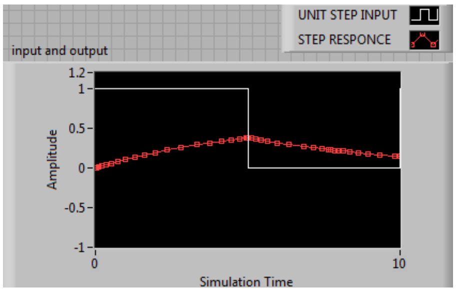


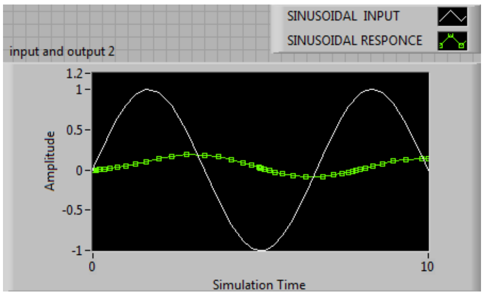
Fig. 32 First Order Gas Process Block Diagram

4.1.3 Results

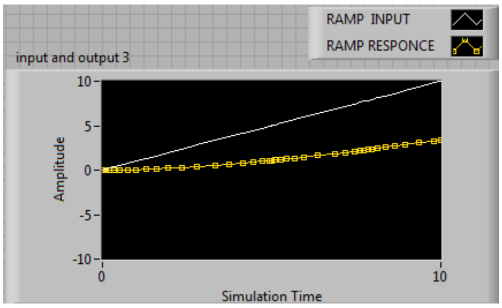
If the signal to the fan increases by 10%, the pressure in the tank will ultimately change by +(10)(K_1)psi. Also, 63.2% change or 0.632(10)(K_1), will occur in one time constant. The obtained responses are shown graphically in Fig. 33, Fig. 34 and Fig. 35 for each of the 3 variables. Clearly, K_1 is the gain that $M_i(t)$ has on P(t), and that τ gives how fast P(t) responds to a change in $M_i(t)$. If the signal to the valve increases by 5%, the pressure in the tank will decrease by (5)K_2 psi. The negative sign in front of the gain indicates this type of response. Now this is can be physically understood as opening the valve, thus extracting more gas from the valve, the pressure in the tank should fall. If the downstream pressure from the valve increases by say, 3 psi, the pressure in the tank will decrease by (3)K_3 psi. That is if $P_1(t)$ changes by +3 psi, P(t) will change by –(3)K_3.



(a)

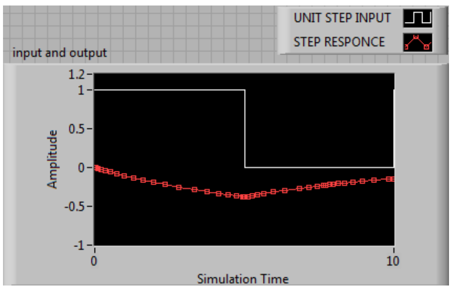


(b)

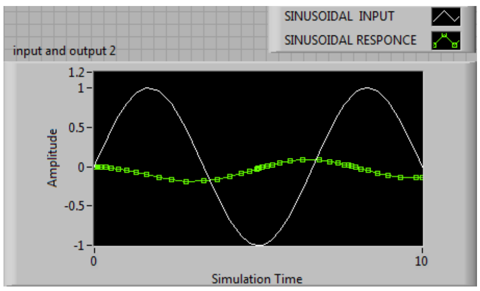


(c)

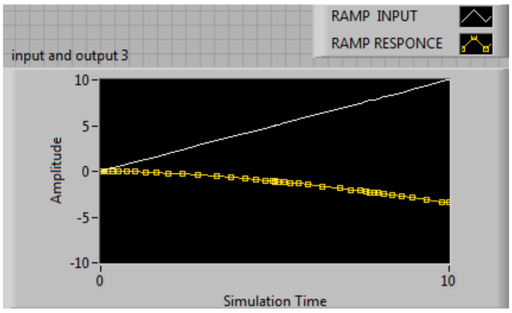
Fig. 33 Response of Signal to Fan $m_i(t)$] to (a) unit step (b) sinusoidal (c) ramp forcing function



(a)

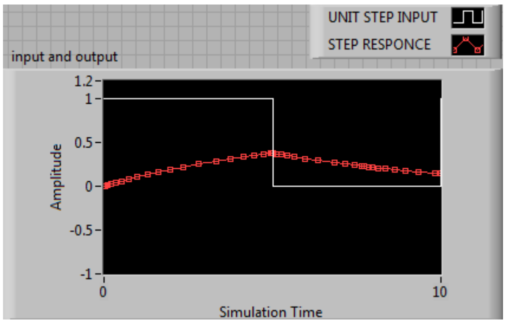


(b)

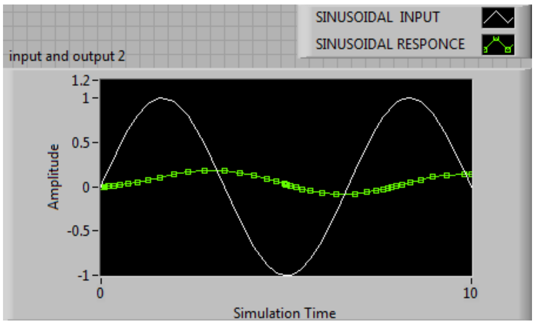


(c)

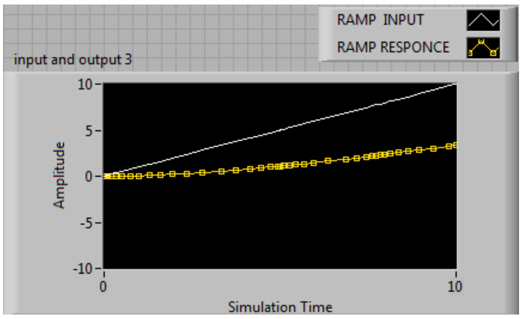
Fig. 34 Response of Signal to Valve $m_0(t)]$ to (a) unit step (b) sinusoidal (c) ramp forcing function



(a)



(b)



(c)

Fig. 35 Response of Downstream Pressure $[P_1(t)]$ to (a) unit step (b) sinusoidal (c) ramp forcing function

CHAPTER-5

CONCLUSIONS

This chapter provides the conclusion about the work and gives suggestion for future work.

5.1 Conclusions

This project comprised of linearization, modelling and analysis of linear as well as non-linear processes such as level, thermal and gas.

The mathematical modelling of each of the process began considering the mass, energy or mole balance. For the case of non- linear models, they were linearized by choosing an appropriate base point around which the Taylor series expansion is done. This was followed by graphical programming of the processes in LabVIEW in order to develop the front panel. The front panel was provided with control knobs to control the variables and plots of the controlled variables against time is obtained as the variables are changed. Following this, the processes were subjected to various input forcing functions i.e. step, input and ramp to obtain the response of the system. The obtained simulation outputs were consistent with the theoretical expected curves which could be deduced by finding out if the system was first, second or third order.

Major Contribution

- Design and simulation of First Order Level Process
- Design and simulation of Second Order (Non-Interacting & Interacting) Level Process
- Design and simulation of Third Order Level Process
- Design and simulation of First Order (Adiabatic & Non-Adiabatic) Thermal Process
- Design and simulation of First Order Gas Process

5.2 Suggestions for Future Work

Future scope of this work can include

- Hardware Implementation of the Front Panel developed in LabVIEW
- Designing of a suitable controller for each Process

- Modelling higher order Thermal and Gas process

5.3 Publications from this Work

Journal:

1. Anuran Maiti, Umesh C. Pati, “Analysis and Control of First and Second-Order Level Process using LabVIEW”, **Accepted** for publication in *Journal of the Instrument Society of India*, June 2013.

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